Nuclear molecular resonances in heavy-ion collisions

Some nuclear scattering phenomena can be attributed to states in which two nuclei are bound to each other at their surfaces, revolving and vibrating for a time before coalescing or disintegrating.

Karl A. Erb and D. Allan Bromley

A significant trend within experimental nuclear physics over the past two decades has been the study, with ever-increasing precision, of the properties of nuclei under various extreme conditions. While such experiments have tended to bring the relatively unstructured many-body features of nuclear systems into the foreground, they have occasionally shown evidence of remarkably simple patterns of motion, even in situations differing drastically from those characterizing the nuclear ground state. We will here consider one such excitation, the quasimolecular mode, in which the nucleus appears to have the form of two smaller nuclei orbiting about each other.

The stability and size of atomic molecules are the results of a balance between the nuclear Coulomb repulsion and an attraction due to the exchange or sharing of an electron. In the case of nuclear "molecules" the balance is between the long-range electrostatic repulsion of the nuclei and the short-range, strong nuclear attraction. This balance is considerably more delicate than the atomic one, and nuclear molecules consequently have only very short lifetimes before the system either dissociates or coalesces into an ordinary nucleus.

These special excitations were first observed by D. Allan Bromley, John Kuehner, and the late Einar Almqvist at Chalk River in 1959 in low-energy collisions between carbon nuclei. They can also be seen in the gamma ray yields measured with the goniometer shown in figure 1. Nuclear encounters at these energies, below about 15 MeV in the lab system, are dominated by Coulomb repulsion and are, in general, only very weakly influenced by the short-range nuclear interaction. For example, in the collisions of carbon nuclei at a center-of-mass energy of 5 MeV, just below the Coulomb barrier where the original quasimolecular phenomena were observed, the classical distance of closest approach on a Rutherford trajectory is some 10.4 fermis, while the radial extent of each of the colliding nuclei is significantly smaller. This situation would appear to leave little scope for nuclear forces in low-energy collisions, and the observed narrow (that is, long-lived) structures in the energy dependence of various cross sections in the sub-Coulomb $C^{12} + C^{12}$ interaction (figure 2) were thus completely unexpected.

The prominence of the resonances represented not only a puzzle for nuclear physics, but also posed a problem in astrophysics. Accurate calculation of carbon burning—a key ingredient in the production of heavier elements in the universe and a process that determines the twilight phases of stellar evolution—depends on a detailed knowledge of the low energy $C^{12} + C^{12}$ cross sections, but the discovery of the resonances rendered extrapolation of the measured cross sections to the lower energies of stellar importance highly uncertain.

Most remarkable, however, was the early demonstration by the Chalk River group that the resonances possess many of the properties of a molecular configuration, but one involving nuclei rather than atoms. The discovery of these phenomena has added a new dimension to the traditional study of both nuclear dynamics and structure, and provided a major impetus to the development of accelerators capable of probing heavy-ion (nucleus–nucleus) collisions with variable energy and precise resolution. And in recent years the study of resonances in heavy-ion reactions has become increasingly more sophisticated, providing not only much more detailed information concerning the properties of the quasimolecules themselves, but also suggesting that the resonances are a much more common aspect of nuclear interactions than had been suspected.

Correlations in the cross sections

An important signature of molecule formation is already evident in the data of figure 2. Resonances occur in the yields of all products of the low-energy $C^{12} + C^{12}$ interaction; moreover, they occur at the same energy in each of the different exit channels and at all angles of observation. Correlations such as these distinguish true resonant behavior from cross-section fluctuations associated with the energy-dependent formation and subsequent decay of randomly overlapping compound-nucleus levels.

Experimentalists have approached the problem of locating and identifying correlated structures in the energy dependence of the cross sections in a variety of ways. Most reaction processes at collision energies near the Coulomb barrier, including those involving particle emission as an intermediate step, eventually result in the emission of at least one gamma ray. The intensity of the total gamma radiation can thus serve as a convenient measure of the total reaction cross section, one in which angular distribution and fluctuation phenomena are

Karl A. Erb is an assistant professor in the physics department at Yale; D. Allan Bromley is Henry Ford II Professor and Director of the A. W. Wright Nuclear Structure Laboratory at Yale.

The gamma ray goniometer at the A. W. Wright Nuclear Structure Laboratory at Yale; it is currently being used to examine inelastic carbon–carbon scattering. D. A. Bromley is checking the alignment of the apparatus before a run. Figure 1

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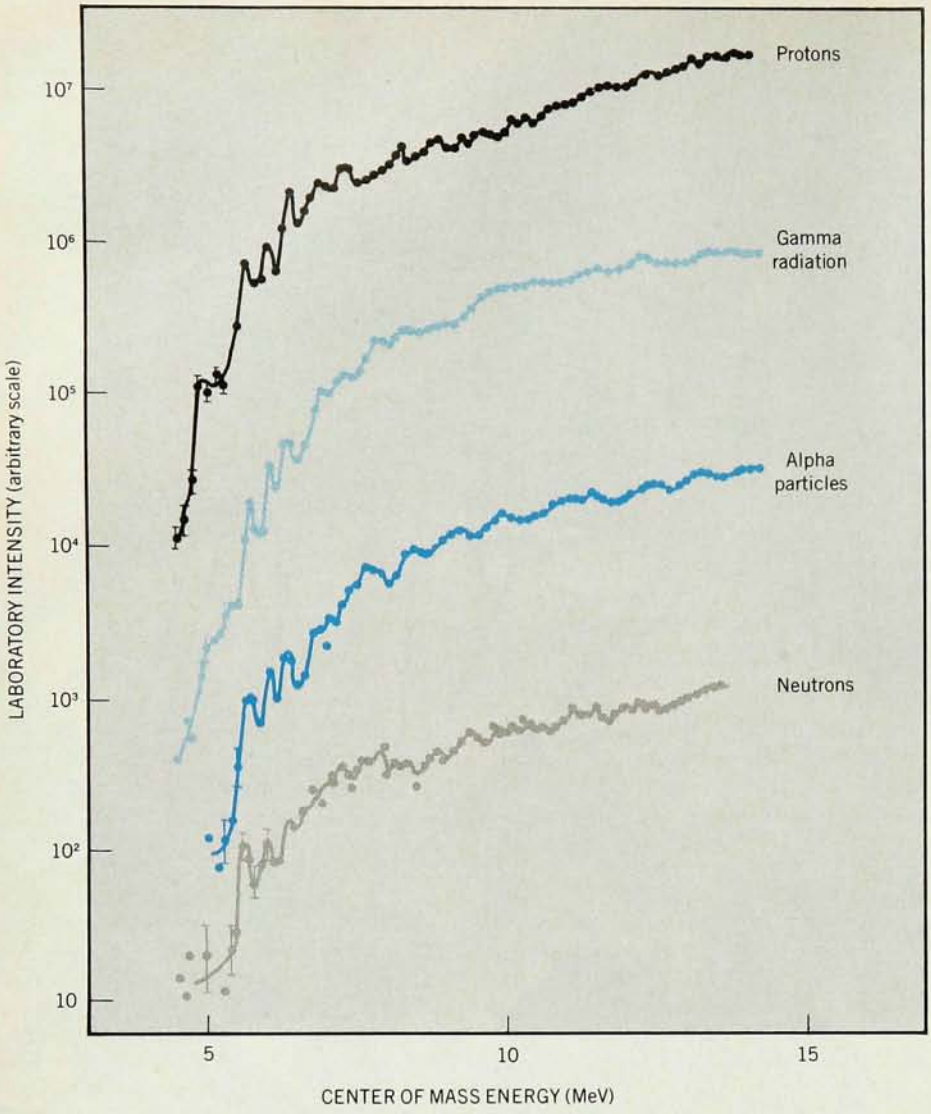


Reaction yields from the $C^{12} + C^{12}$ interaction from the original Chalk River work on nuclear molecular phenomena. The curves show data for various reaction channels. Figure 2

almost entirely masked. The actual association of these cross-section maxima with the formation and decay of a nuclear molecule must, however, satisfy the much more specific criteria discussed below; for the present we note only that these additional criteria have been met by a number of structures appearing in the low-energy interactions of the carbon–carbon and other light nuclear systems.

The nuclear structure factor

At energies well below the Coulomb barrier the nuclear cross sections decrease precipitously with decreasing Coulomb barrier penetrability, making deviations from normal behavior (and also discrepancies among different sets of experimental data) extremely difficult to detect. For this reason, data at these energies are customarily presented in terms of the nuclear structure factor, $S(E)$, which is obtained by removing an estimated penetrability factor, $P(E)$, from the measured yields:

$$\sigma(E) = S(E) \cdot P(E)/E$$

The extent to which this procedure serves to isolate the interesting aspects of the cross-section behavior for further study is illustrated in a comparison of the energy dependence of the carbon–carbon structure factor shown in figure 3 with that of the corresponding cross sections (figure 2). The latter change by more than four orders of magnitude in the energy region under consideration, but this systematic variation is reduced in the structure factor to a relatively flat background against which the resonances emerge clearly.

The carbon–carbon structure factor plotted in figure 3 is based on measurements made by groups at the California Institute of Technology and the University of Pennsylvania in addition to those made originally at Chalk River. These results, particularly those from Pennsylvania, showed an increase in the structure factor at energies low enough to approach thermal energies within a star in its carbon-burning phase. Extrapolation of the data to thermonuclear energies yielded a carbon burning rate substantially higher than any that could be encompassed within current models of stellar evolution. Subsequent remeasurements of the low-energy cross sections determined that the earlier low-energy data were in error and that whereas the sharp, resonant structures continue to appear even at the lowest energies measureable, no monotonic increase in the structure factor occurs.

Before proceeding to a discussion of measurements that identify the resonances in the barrier region as being quasimolecular in nature, we note for future reference the difference between the carbon–carbon and oxygen–oxygen structure factors plotted in figure 3. Differences in the overall shape of the "background" can be seen, and to a certain extent these may arise because somewhat different penetrabilities, $P(E)$, were employed in reducing the cross-section data in the two figures. In part because of these possibly artificial differences, it is not yet clear whether useful information is contained in the background. Beyond this, however, the absence of dramatic, sharp, resonance structures in the oxygen–oxygen system is evident and emphasizes that we must explain the appearance of structure in some systems and its apparent absence in others. We shall return below to a discussion of these and related consequences of the interplay between the resonances observed in the scattering process and the properties of the host nuclei.

Detailed molecular signatures

The striking exit-channel correlations discussed in connection with figure 2 indicate the formation of a prominent resonant configuration in the course of the carbon–carbon interaction, but the identification of that configuration as quasimolecular depends on more specific observations.

The lifetimes, τ, of the resonances, as inferred from their total energy width, Γ, where $\tau = \hbar/\Gamma$, are typically 5×10^{-21} sec, and thus correspond to an interval some 5 to 10 times longer than the collision time. These resonance lifetimes are sufficiently long to signal the formation of an entity quite distinct from the initial configuration (non-interacting, distant, carbon-12 nuclei), but they are far too short to permit the study of any sort of "nuclear molecular chemistry." We must employ other means if we are to learn about the structure of the resonances.

For our purposes, it will be convenient to characterize a resonance in terms of its spin, its total width, Γ, (equivalently an inverse total decay rate) and its partial widths, Γ_r, for decay into various individual configurations or channels, r. These partial widths represent a measure of the structural overlap between the resonance itself and the rth channel (but reflecting also the dynamical properties of the channel). Near a resonance it usually suffices to define only two channels, elastic and total. In that case, we can determine the two partial widths, once the spin is known, from the mea-

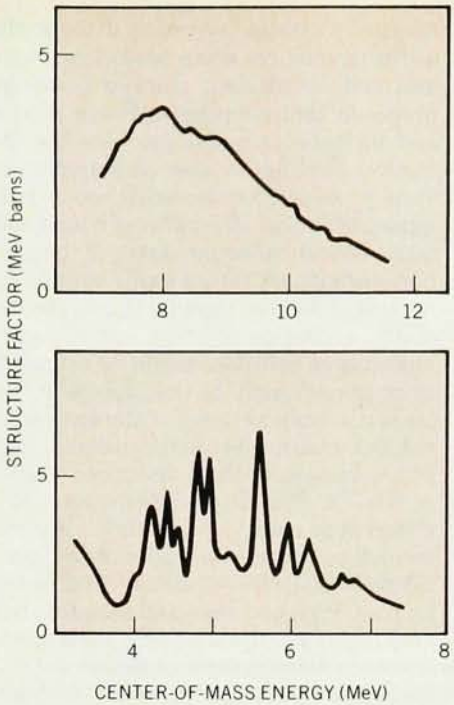
sured cross-section by using the Breit–Wigner formula together with the fact that the total width is the sum of all the partial widths. And we can frequently determine the spin of a resonance from the angular distribution of its decay products.

As an example of typical experimental data that display resonant structure and yield its spin, we consider data obtained by our group at Yale in a study of C^{12} (C^{12}, α) Ne^{20} yields in an energy region where three resonances, with spins of $4\hbar$, $6\hbar$, and $8\hbar$, had been predicted by a Kyoto University group. We measured differential cross sections for alpha particles, as functions of energy and angle, for several different excited states of the remaining neon-20 nucleus. The angle-integrated, or total, cross sections for several exit channels appear as functions of energy in the left panel of figure 4, while the angular distributions for the Ne^{20} ground-state exit channel are plotted on the right. A number of maxima possibly deserving additional study can be identified in the total yields, but few of them are correlated from channel to channel; the remainder are very probably examples of compound-nucleus fluctuations of the type mentioned above. The maximum at 7.71 MeV, however, exhibits the correlations required of a true resonance; moreover, the angular distribution in the ground-state exit channel (figure 4b) changes from being rather featureless, at energies on either side of this maximum, to a pure $P_4^2(\cos\theta)$ shape at the maximum, indicating unambiguously that the resonating structure has a spin of $4\hbar$. Helmut Voit and collaborators at Erlangen in extensive experiments of this kind have measured spins for almost all of the resonances appearing in the total reaction cross section near the Coulomb barrier.

Estimates based on statistical models (in which each channel is presumed to be populated strictly according to its phase space and penetrability factors) are typically fifteen times smaller than the measured partial widths for decay to the carbon–carbon channel. The observed magnitudes of the partial widths thus represent a quantitative experimental determination that the resonances result from the formation of a carbon–carbon nuclear molecule rather than a mere statistical fluctuation.

Statistical studies

A very essential part of the overall study of nuclear molecular phenomena has involved their isolation from other aspects of nuclear interactions that might be mistaken for them; we have just discussed the question of unique molecular signatures. Of particular interest and importance has been the question of energy-dependent structures in cross sections that in many cases might be—and sometimes have been—mistaken for molecular resonances.



Structure factor for (a) $O^{16} + O^{16}$ and (b) $C^{12} + C^{12}$ elastic scattering. The data are from work done at Chalk River, Cal Tech and Pennsylvania. Removing the slowly varying barrier-penetration factor from the measured yields brings out the striking differences between scattering with resonances (carbon–carbon) and without (oxygen–oxygen). Figure 3

A statistical model originally developed by Walter Hauser and Herman Feshbach for interactions involving light nuclei has also proved useful for investigating these heavy-ion collisions. Groups at Yale and elsewhere have applied the Hauser–Feshbach model to the $C^{12} + C^{12}$, $C^{12} + N^{14}$, $C^{12} + O^{16}$, and $O^{16} + O^{16}$, and many other systems. Their results show that the carbon–carbon interactions, and, to a lesser extent the carbon–oxygen interaction, involve few competing channels, so that the molecular resonances are clearly evident. For the other systems, competition smears out the resonances, which then tend to merge into the background.

The statistical analyses appear able to account, with reasonable probability, for much of the fluctuating structure observed in the data. This emphasizes that before non-statistical assignments can be suggested it is essential that substantial evidence be adduced for them. Indeed it is fair to note that considerable pollution of the literature has resulted recently from the tendency to ascribe essentially *any* rapid energy dependence of the reaction cross section to molecular resonances. Simple observation of such energy dependence is *not* adequate to permit such a conclusion.

Molecular dynamics

Once the resonances are established, their distribution in energy can serve to provide information about the internal motions of the carbon–carbon molecule. As we shall see, resonances of a given spin are clustered within an energy region a few MeV wide, and the energy centroids of these clusters define a locus that is characteristic of rigid rotation, with energy proportional to $J(J+1)$.

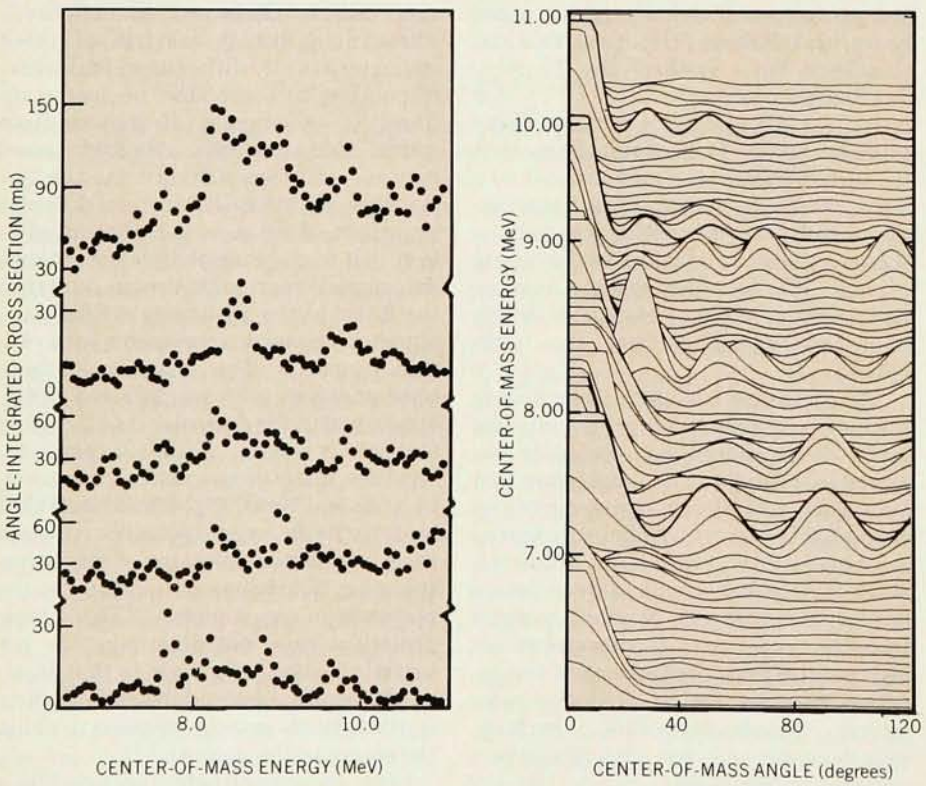
Graphs plotting partial widths of molecular channels, derived from data such as those shown in figures 3 and 4, often display a clustering of low-energy resonances with a particular spin. As data from higher energies have become available, particularly from the work of Eric Cosman at MIT and Neil Fletcher at Florida State, they have also displayed such clusters, but with larger angular momenta. In many of these cases, however, there are as yet not sufficient data to establish the existence of true resonances, so that the evidence for molecular clusters is not as clear as it is at low energies.

The $C^{12} + C^{12}$ elastic scattering should reflect, more strongly than any inelastic channel, the presence of a carbon–carbon molecular rotational band and thus is the logical process to examine for direct evidence of any such phenomenon. Following the discovery by James Maher and his collaborators at Yale of pronounced gross structure ($\Gamma \sim$ 2–3MeV) in the elastic scattering of O^{16} by O^{16}, a series of systematic measurements covering a wide energy range were initiated at Yale for the $C^{12} + C^{12}$ and other systems in the late 1960's. The 90-degree data from the first of these $C^{12} + C^{12}$ measurements are combined with earlier Chalk River low-energy data in the lowest plot in figure 5. These data display maxima of three characteristically different widths—corresponding to compound nuclear reactions, to resonances of intermediate width, and to gross structure resonances—and thus demonstrate the importance and interplay of several different properties of the carbon–carbon interaction. (It must be emphasized that these data already represent averages, and that the finest of the structures are only apparent in careful measurements with very thin targets.) The analysis of these phenomena as they are reflected in the elastic-scattering data may lead to highly ambiguous results. To avoid these ambiguities, many groups instead construct, by trial and error, a potential well that leads to the observed scattering. One can then inspect the solutions of the corresponding Schrödinger equation for the presence of resonances. (The fitting procedure does not determine the potential uniquely, of course, so that ambiguity remains; but additional physical considerations may be invoked to aid in the choice of the potential.[4])

Such an optical potential provides a convenient parametrization of the energy averaged, or macroscopic, properties of the nucleus–nucleus interaction, and it should be constructed with reference only to the more slowly varying aspects of the elastic data. The relevant cross sections

for the $C^{12} + C^{12}$ system are prepared by averaging the data over progressively wider energy intervals until the fine- and intermediate-width structures disappear. A well-defined gross structure that can be reproduced as scattering from a macroscopic potential, emerges clearly in these energy-averaged yields. Adriano Gobbi and his collaborators at Yale devised an appropriate optical potential to fit these results. The subsequent analysis of the potential scattering indicates that the gross structures are due to the existence of a molecular rotational band at high excitation in magnesium-24. The trajectory and width of the elastic molecular band extracted from the Yale potential by theorists at Brookhaven and at Frankfurt is represented by the shaded region of figure 6, where resonances seen in elastic scattering are also presented for comparison. The moment of inertia associated with the band is found to be nearly twice that characteristic of the Mg^{24} ground-state rotational band, and corresponds closely with a classical estimate for two peripherally touching, but rigidly rotating, carbon nuclei.

A final, and most important, point remains: If the observed resonances originate with a molecular band based on rotations of quasi-bound carbon nuclei, what is the role of the collective excitations of the constituent nuclei? This question was raised very early in the study of the resonances when Mokichiro Nogami and his student Bunryu Imanishi proposed that coupling between elastic and inelastic channels provides the effective binding in the carbon–carbon system needed for the existence of molecular behavior. A number of bound and quasi-bound collective states of the carbon nucleus are rather easily excited in nuclear collisions, in general, and the inelastic excitation of these states in carbon–carbon collisions might be expected to couple strongly to the molecular behavior, if only because of the increased nucleus–nucleus interaction time implied by the unusually small resonance widths ($\tau = \hbar/\Gamma$). The first excited state of C^{12} occurs at an energy of 4.43 MeV. It is the second member of a well-defined quadrupole collective rotational band based on the C^{12} ground state and therefore has very large inelastic scattering matrix elements connecting it to that ground state. Its excitation in the resonant carbon–carbon interaction has been studied by groups at Stony Brook, Yale, and elsewhere and exhibits a very pronounced gross structure reminiscent of that observed in the elastic scattering (figure 5). Similarly, the cross sections for reactions in which both nuclei are excited to 4.43 MeV (mutual excitation) are also seen to resonate strongly. The gross structure of the inelastic yields is quite dramatic: the 100–150 mb contained in the single-excitation yields corresponds to 10–15% of the total reaction cross section. The inelastic processes clearly play a key role in the resonant process, and any theory must take them into account.



A typical search for molecular resonances in the C^{12} (C^{12}, α) Ne^{20} reaction. The left panel shows angle-integrated cross sections as functions of energy for the reaction channels populating the four lowest states in Ne^{20}: the 0^+ ground state and excited states at 1.63 MeV (2^+), 4.25 MeV (4^+), 4.97 MeV (2^-). The colored curve shows the sum of the cross sections in the four channels. The right panel displays differential cross sections plotted as a function of both energy and angle for the same reaction. Heavy curves indicate measurements corresponding to specific resonances seen in the data from the left panel. Figure 4

Macroscopic theoretical models

The original Chalk River results (figure 2) and their subsequent experimental development and extension at Chalk River, Pennsylvania and Cal Tech stimulated the development of a large number of theoretical models to reproduce and explain the existence of nuclear molecular phenomena.

To reproduce the location and widths of the observed resonances in any potential model it was necessary to have a large real potential radius (corresponding to the large partial widths) and small imaginary potential depth (corresponding to the long lifetimes). In the original model, developed by Erich Vogt and Hugh McManus, the large oblate deformation and large deformability of C^{12} were the key elements in obtaining the desired characteristics in the $C^{12} + C^{12}$ system. The model was not detailed enough to allow any quantitative predictions. It did, however, serve to highlight a number of the essential characteristics of subsequent models as well as suggest a marked dependence upon the internal structure of the nuclei involved.

By far the most successful of the early models was that originally suggested by Nogami and developed by Imanishi at the University of Tokyo. Central to this model was the concept of temporary conversion of kinetic energy of relative motion into internal excitation of one or both of the interacting nuclei; with such a model Imanishi succeeded, in 1968, in fitting both the observed locations and widths of the original three Chalk River resonances. But in doing so he required what, at the time, was considered an unphysically small imaginary potential depth of 150 keV.

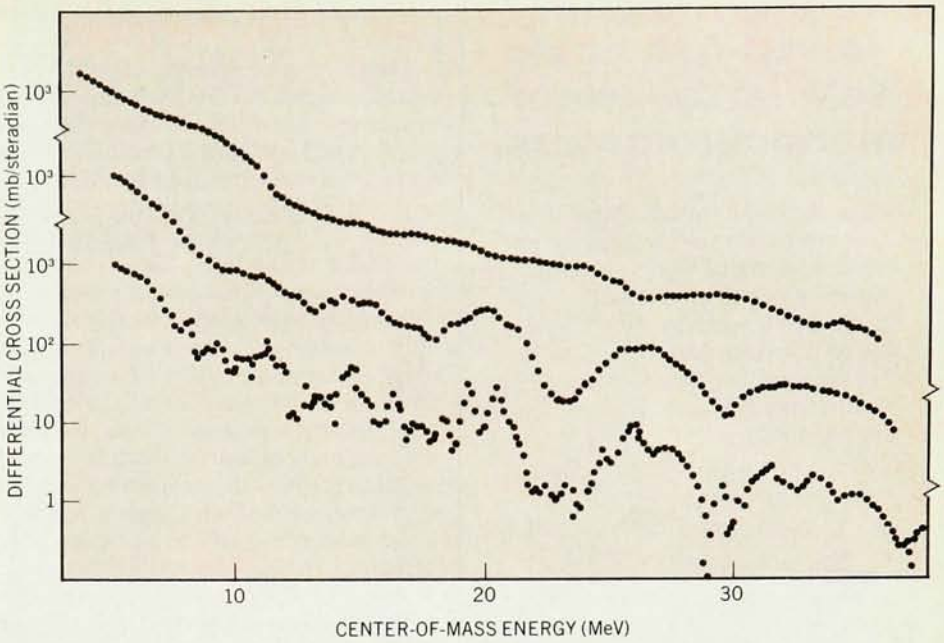
Figure 7 illustrates a number of features of the potential models. In all non-central collisions the resultant interaction potential reflects the sum of the repulsive long-range Coulomb interaction, the short-range nuclear interaction and the repulsive centrifugal pseudopotential.

These potentials are, of course, analogous to the Morse potential for interatomic interactions, but there are significant differences. In the Morse potential the central repulsive core that excludes even the lowest partial waves from very small radii appears naturally as a consequence of the exchange mechanisms invoked; in the nuclear case the origin of the central repulsive core is much less obvious. Although there is clearly a repulsive core in the underlying nucleon–nucleon interaction, heavy-ion interactions

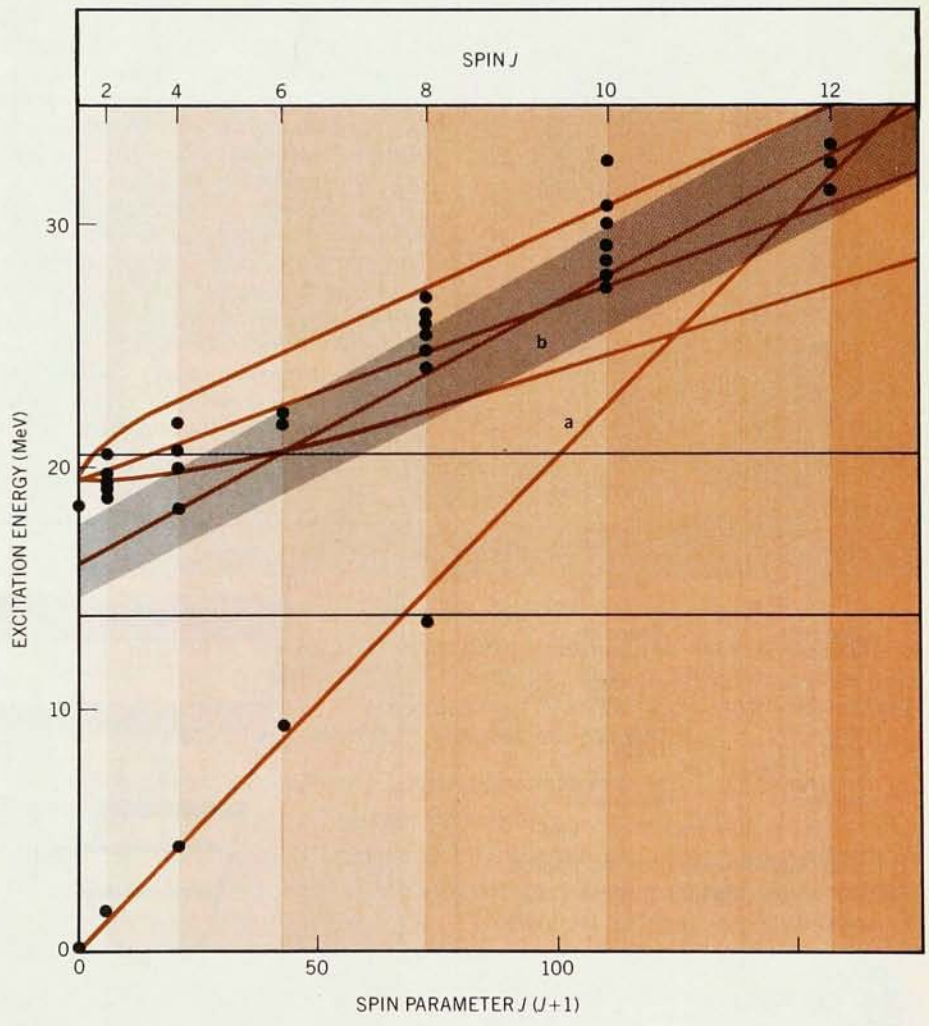
appear to be insensitive to it. There is evidence that the Pauli principle can provide an effective nuclear repulsion. The exact details of the central region of the real nuclear potential in nuclear molecular phenomena, however, remain shrouded in both absorption and mystery. Much higher energies than any now available with precision will be needed to lift this veil. At the energies thus far studied in detail, a minimum such as that shown in figure 7 appears in the resultant potential; at higher energies the rapidly increasing angular momentum—hence centrifugal potential—removes the minimum entirely. Obviously the exact form of the potential is different for each angular-momentum partial wave. We have suppressed the differences for clarity in figure 7.

Four different classes of resonance phenomena are indicated in the figure. Energy E_1 illustrates a resonance arising from simple tunnelling into a quasibound state of the potential; energy E_2 illustrates an orbiting or shape resonance (the terms are here synonymous) arising from a virtual state of the potential. In such a state the incoming particle effectively orbits for some time at a radius close to that of the lip of the real potential. At energy E_3 an interaction during the collision excites one (or both) of the nuclei involved to an internal quantum state at higher energy, and the relative kinetic energy decreases by a corresponding amount. If the potential is such that this new temporary energy of relative motion coincides with that of a quasibound state in the potential, then a resonance would be expected. This is the process used by Nogami and Imanishi to model the behavior of the $C^{12} + C^{12}$ system.

The energy E_4 corresponds to another orbiting resonance in the potential. Because the two nuclei spend a greatly increased time in close proximity in such a state, the probability of internal excitation is correspondingly increased. If the potential is such that this excitation drops the relative energy to match that of a quasibound state in the potential, then a *double* resonance occurs. Since each individual resonance component (virtual and intrinsic) is characterized by its own angular momentum, coupling of these angular momenta in the double resonance would fragment the total resonance into a number of components, the number depending the exact angular momenta involved. Using this double resonance model in full coupled-channel calculations Walter Greiner and his associates at Frankfurt have succeeded in obtaining very reasonable qualitative, and in some areas, quantitative fits to elastic scattering excitation functions in both the carbon–carbon and oxygen–oxygen systems; the general features of the inelastic cross sections corresponding to the invoked channels in the model are also reproduced. Their work has been basic to all



Differential cross section for elastic carbon–carbon scattering measured at 90 degrees. The lowest curve shows the data obtained in experiments at Yale and at Chalk River. The upper curves are derived from this one by averaging the data over energy intervals of 2 MeV and 10 MeV, thus bringing out the broad structure and smooth background of the excitations, respectively. Figure 5



Rotational structure of excitations in magnesium-24. The black data represent experimentally observed resonances. The elastic rotational band determined from the optical potential is indicated in gray. The colored curves are schematic plots of an initial calculation by Abe, Kondo, and Matsuse with a double-resonance model. Curve **a** is the ground state rotational band; curve **b** is the elastic molecular band; the other curves represent other predicted rotating structures in which one of the carbon nuclei is in an excited state. Figure 6

subsequent developments of the molecular models.

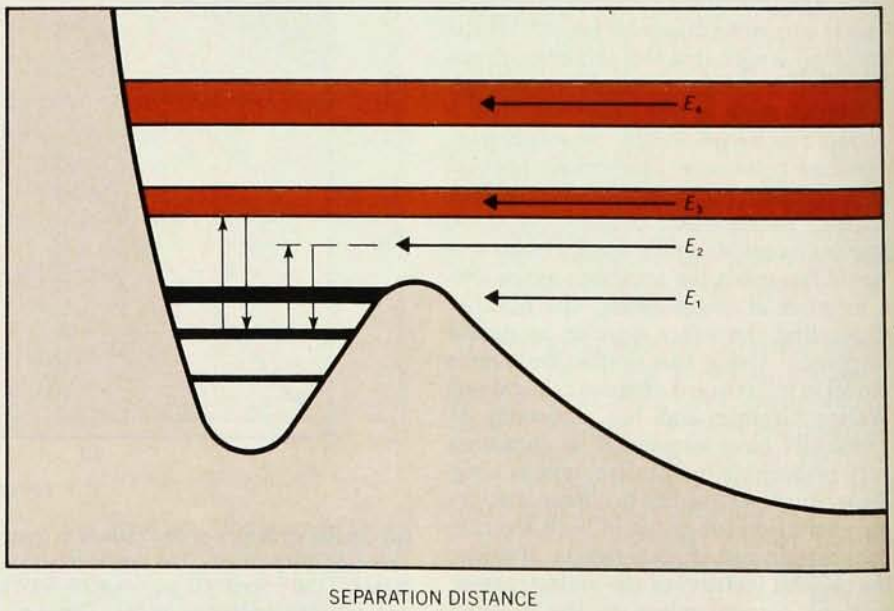
Thus far we have focussed on the *real* potential; also of importance is the imaginary potential representing absorption and non-elastic phenomena. In his original work Imanishi found that he required an imaginary well depth of only 150 keV—a value widely regarded as unreasonable at the time. Greiner and his collaborators subsequently succeeded in putting this shallow imaginary potential on a sound physical basis by noting that in the region of excitation where molecular states have been observed the nuclear level density is extremely low. Because the imaginary potential depth is proportional to the level density, it also is small, and in effect a window exists through which we can observe the molecular phenomena.

Yasuhisa Abe, Yosio Kondo and Takehiro Matsuse from the University of Kyoto have taken the double resonance model to its logical conclusion by including all possible excitation modes. Their work has provided a major stimulus to the entire field. In an initial study of the C^{12} + C^{12} interaction, including *only* excitation of *one* C^{12} to its lowest 2^+ state at 4.43 MeV, they succeeded in reproducing the qualitative—and many of the quantitative—aspects of the data in the barrier region. And, most important, they made a host of specific predictions, some of which have since been confirmed.

Figure 6 shows, very schematically, the results of this initial calculation on an energy–angular-momentum diagram chosen so that simple rotational bands appear as linear loci of the form $E_J = AJ(J + 1) + E_0$. The energy E_0 is the minimum excitation energy of the rotating structure, A is inversely proportional to its moment of inertia, and J is the total angular momentum of the state in question. (In such a simple picture a rotational band is composed of states all of which have identical internal structure and differ only in the quantized angular velocity with which this structure is rotating.) The figure shows five distinct rotational bands. The lowest, the usual ground state band of Mg^{24}, is experimentally confirmed up to its 8^+ member and we have simply used a Regge trajectory to extrapolate to higher J values; the measured moment of inertia of the Mg^{24} prolate-spheroid ground state corresponds to A = 205 keV.

The higher-energy elastic-scattering data demonstrate the existence of another rotational band for Mg^{24}. The experimental results are in remarkable accord with theoretical predictions based on an internal structure consisting of two ground-state carbon nuclei bound into a molecular complex. The moment of inertia for this state, corresponding to a value of 110 keV for A, is almost twice what it is for the ground state of Mg^{24}, and is thus entirely consistent with the proposed structure. Experiments have very probably confirmed the existence of members of this band with angular momentum up to $20\hbar$ (the assignments are not yet entirely definite), and we are confident that when higher energy accelerators become available, they will produce states with higher angular momenta belonging to this band.

Also shown in this figure are predictions for three "excited" rotational bands wherein one of the C^{12} nuclei is excited to its 2^+ state at 4.43 MeV. The separation in energy among the bands reflects the angular momentum coupling between the orbital and intrinsic motion noted above. Although only fragmentary evidence is available as yet, the moment of inertia of



Schematic interaction potential for heavy ions. The excited states and bands are indicated in color; the arrows show the possible excitation energies discussed in the text. Figure 7

the excited configuration in these bands, corresponding to $A = 75$ keV, is three times that of the Mg^{24} ground state.

Obviously the three excited bands in this figure are only illustrative of the vastly greater number that correspond to one or both of the interacting nuclei being in higher excited states. Greiner and his coworkers have noted, as mentioned above, that there is an effective window lying just above the "yrast line" (the locus of lowest states having a given angular momentum) through which molecular resonances would be detectable. Within this window the density of states of the required angular momentum, hence the corresponding imaginary potential strength is very small; the nucleus is effectively transparent, as is required for the observation of molecular phenomena. Moving up in excitation from the yrast line, however, this transparency rapidly decreases and molecular phenomena are expected to be smeared beyond recognition.

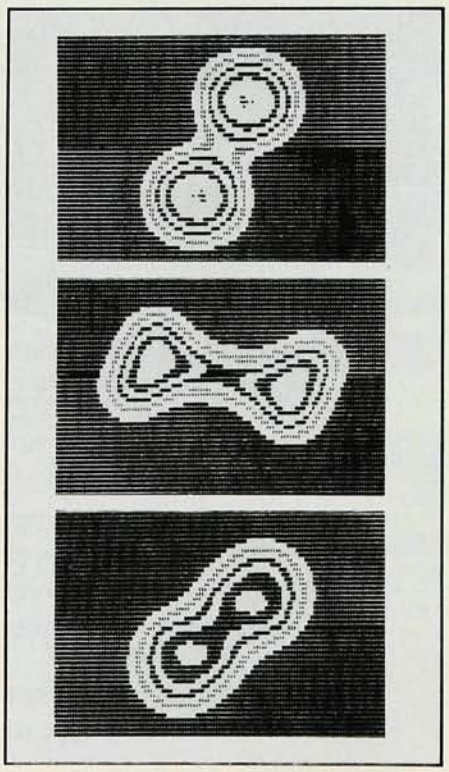
Recently, Herman Feshbach, at MIT, has suggested that the elastic molecular resonances may be classic examples of the "doorway-state" concept, which he and his associates introduced a number of years ago to explain certain characteristic effects in reactions induced by light ions. The idea is that a specific state, the doorway, is formed from the interaction entrance channel; subsequently this either dissociates to yield elastic scattering or, through appropriate coupling mechanisms, moves sequentially through ever more complicated configurations toward the thermodynamic equilibrium characteristic of a compound nucleus. The molecular doorway is centered on the resonance and is coupled *weakly* to the underlying continuum of more complex states. Depending upon the detailed structure of these underlying states, the doorway states couple preferentially to different exit channels; for the $C^{12} + C^{12}$ interaction the exit channels would include protons plus sodium, alpha particles and neon, and Be^8 plus O^{16} as well as the inelastic carbon–carbon channels discussed above. This coupling would then be reflected in the appearance, in each of these exit channels, of a cluster of relatively sharp resonances within the envelope of the original doorway state and sharing its strength. Such clusters have been observed in many channels but detailed measurements on their strength are only beginning.

Microscopic models

Much more recent, but in parallel with the above-mentioned successes with macroscopic models, have been the efforts to understand molecular phenomena in terms of the nucleons rather than the nuclei involved. Two quite distinct approaches have been taken. One of these is based on nuclear shell models, the other on self-consistent nuclear fields. We will

here focus our attention on the latter.

It is as yet impossible to solve the fully microscopic Schrödinger equation for situations as complex as the collision of two large nuclei. To approximate the behavior of the system one can consider the motion of each nucleon in the mean field produced by the others; the Schrödinger equation for this effectively single-particle problem can be solved in a self-consistent fashion according to the Hartree or Hartree–Fock method. The solution yields density profiles and other collision characteristics for successive instants in time. Ronald Cusson and Joachim Maruhn at Oak Ridge and Hubert Flocard, Steven Koonin and Morton Weiss at the Lawrence Livermore Laboratories have performed detailed Hartree–Fock calculations, for $C^{12} + C^{12}$ and $O^{16} + O^{16}$, respectively. In both cases the results show clearly the formation of a molecular bond during the collision, with the two nuclei rotating or vibrating about this bond for an appreciable length of time (figure 8). Computer-memory limitations in both cases precluded following the collision through to the breakup of the molecular compound. Henry Tang of Yale and Cheuk-Yin Wong of Oak Ridge have recently set out to perform a more complex Hartree–Fock calculation that includes individual nucleon–nucleon collisions in which each nucleon can change its orbital. Their results are not yet available.



Collision between two oxygen-16 nuclei at 52.5 MeV. The figure shows contour lines for the nuclear density intervals of about 7.10^{-22} sec. The results are from a three-dimensional Hartree–Fock calculation by Flocard, Koonin and Weiss of Lawrence Livermore. Figure 8

These time-dependent Hartree–Fock calculations have already provided a clear physical picture of the collision development; it will be interesting to find what modifications are produced in these pictures by the inclusion of specific nucleon–nucleon collisions.

Calculations involving shell models give analogous predictions. Again, the nuclei develop a rotational band corresponding to a deep inner well arising from the normal ground state and an elastic molecular band in a shallow outer well. There is a rather striking parallel here with the situation now known to exist in isomeric fission, where again there is an equilibrium potential minimum corresponding to the fissionable nucleus in its ground state and a second, but higher-energy, minimum at larger deformation in which the system can reside temporarily before either dissociating outward to yield fission or back inward to yield the original nucleus and a gamma ray. Residence in the outer minimum is again extremely short lived but extremely long by the normal fission time scales. This is a particular example of the extent to which properly chosen heavy-ion collisions can be considered as an inverse fission phenomenon that is susceptible to much greater experimental control and can illuminate many facets of the fission mechanism.

It is gratifying that the microscopic calculations thus far carried out—without *ad hoc* adjustments of parameters or situations—appear to lead to macroscopic predictions in accord with the available experimental data and in doing so provide a better understanding of some of the physics underlying the successes of the earlier macroscopic models.

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